The Successful Prediction of the Extrasolar Planet HD 74156 d

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ABSTRACT

Most of the first-discovered extrasolar multi-planet systems were found to lie close to dynamically unstable configurations. However a few observed multi-planet systems (*e.g.* HD 74156) did not show this trait. Those systems could share this property if they contain an additional planet in between those that are known. Previous investigations identified the properties of hypothetical planets that would place these systems near instability. The hypothetical planet in HD 74156 was expected to have a mass about equal to that of Saturn, a semi-major axis between 0.9 and 1.4 AU, and an eccentricity less than 0.2. HD 74156 d, a planet with a mass of 1.3 Saturn masses at 1.04 AU with an eccentricity of 0.25, was recently announced. We have reanalyzed all published data on this system in order to place tighter constraints on the properties of the new planet. We find two possible orbits for this planet, one close to that already identified and another (with a slightly better fit to the data) at ~ 0.89 AU. We also review the current status of other planet predictions, discuss the observed single planet systems, and suggest other systems which may contain planets in between those that are already known. The confirmation of the existence of HD 74156 d suggests that planet formation is an efficient process, and planetary systems should typically contain many planets.

Subject headings: methods: N-body simulations, stars: planetary systems, stars individual: HD 74156

1. Introduction

The detection of extrasolar planets has provided an unprecedented opportunity to test models of planet formation. One such model is the "Packed Planetary Systems" (PPS)

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hypothesis (Barnes & Raymond 2004 (hereafter RB04); Raymond & Barnes 2005 (hereafter RB05); Raymond *et al.* 2006; Barnes & Greenberg 2007; see also Barnes & Quinn 2001, 2004) which posits that, between the innermost and outermost giant planets, planetary systems formed such that they were filled to capacity; an additional planet would create an unstable system. Other investigations gave consistent results (*e.g.* Rivera & Lissauer 2000; Bois *et al.* 2003; Goździewski *et al.* 2006). These analyses were grounded in considerable theoretical work to examine the (in)stability of planetary systems (*e.g.* Chambers *et al.* 1996; Weidenschilling & Marzari 1996; Ida & Lin 1997).

The PPS hypothesis was suggested because five of the first six known extrasolar multi-planet systems showed evidence for packing: υ And (Butler *et al.* 1999), 47 UMa (Fischer *et al.* 2002), GJ 876 (Marcy *et al.* 2001b), HD 82943 (Mayor *et al.* 2004), and HD 168443 (Marcy *et al.* 2001a) were packed (Barnes & Quinn 2001, 2004; BR04), but HD 74156 (Naef *et al.* 2004) was not. This high frequency of packing suggests that it must be a common feature of planetary systems. The PPS hypothesis takes this suggestion a step further and proposes that all planetary systems have tended to form dynamically full.

For the PPS model to be correct, then seemingly non-packed systems require at least one additional planet to fill them up. This conjecture led BR04 and RB05 to search for stable regions in between known planets in several systems, including HD 74156. These investigations presumed that, by identifying a stable region in between the known planets, it would be possible to predict the mass and orbit of a previously unknown planet. BR04 explained the reasons to expect additional planets and outlined how to predict planets through numerical simulations of test particles. RB05 then placed massive companions in the gaps identified in BR04 in order to predict the likely orbital elements of planets that could be detected. Note that BR04 used the initially reported orbital elements and found HD 74156 was packed. RB05 used the revised orbits, published in Naef *et al.* (2004), and found the system was not packed.

An additional planet would require a mass and orbit that guaranteed dynamical stability for the age of the system. The greatest difficulty with such an analysis is that the size of the stable zone and the mass of the hypothetical planet are degenerate; lower mass planets have a wider stable zone, larger planets have a narrower zone. In order to estimate the mass, RB05 considered the mass of the two known planets. As both these planets are larger than Jupiter (2 and 8 Jupiter masses), then a planet in between the two would also need to be large in order for the protoplanetary disk to have a plausible surface density profile (*e.g.* a power law). At the same time, the mass would have to be small enough to have avoided detection by the initial observations. In order to help quantify the predicted mass of the hypothetical planets, RB05 considered Saturn-mass, Jupiter-mass and 10 Jupiter-mass

objects. They found the HD 74156 system had an 80% probability of being able to support a Saturn-mass planet, a 40% probability for a Jupiter-mass planet, and a 10% probability of 10 Jupiter-mass planet. The larger masses would likely have been detected previously, so RB05 settled on a Saturn mass as the likely mass of the putative companion.

Bean *et al.* (2008) discovered HD 74156 d, an extra-solar planet with a mass 40% greater than Saturn, at 1.04 AU with an eccentricity of 0.25. This planet is consistent with the PPS model: RB05 predicted a Saturn-mass planet with semi-major axis, a, in the range $0.9 \lesssim a \lesssim 1.4$ AU and eccentricity, e, in the range $0 \leq e \lesssim 0.2$. Here we reanalyze all available data for HD 74156 (§ 2), discuss the current status of the PPS model in § 3, and draw general conclusions in § 4.

2. The Orbit of HD 74156 d

The best-fit orbits published by Bean *et al.* (2008) for the planets orbiting HD 74156 are actually unstable on $\sim 10^5$ year timescales. The instability arises due to strong gravitational interactions resulting from close approaches between the inner two planets, b and d. In this section we consider all published observations and identify four plausible stable fits to the data.

Currently, all published radial velocity (RV) data for HD 74156 appear in papers by Naef *et al.* (2004) (51 observations gathered with the ELODIE spectrometer with a mean dispersion of 12.7 ms^{-1}, and 44 measurements of CORALIE with a mean dispersion of 8.5 ms^{-1}), and in Bean *et al.* (2008), who published 82 precision measurements from the Hobby-Eberly Telescope (HET), with mean dispersion of 2.7 ms^{-1}. The combined data set covers $\sim$ 9.33 yr. We binned a few measurements in the CORALIE and ELODIE data sets which were done during one night. We also shifted ELODIE and CORALIE observations with respect to the mean RV in both set. We rescaled data errors by adding jitter of 4 ms^{-1} in quadrature. In all calculations, we adopted the mass of the parent star to be 1.24 M$_\odot$, following Naef *et al.* (2004). This procedure is slightly different than (but consistent with) that in Bean *et al.* (2008).

First, we searched for the best Keplerian fits to the combined data set with the hybrid optimization code (Goździewski & Migaszewski 2006) relying on the genetic algorithm (Charbonneau 1995). Because the number of planets in the system is unknown, we considered models with two, three and four planets. The so-called velocity offsets of the telescopes are the free parameters in the model. Hence, the N-planet model depends on $5N + 3$ primary parameters, *i.e.* tuples (K, P, e, ω, τ) comprising of velocity amplitude K in ms^{-1}, orbital

period P in days, eccentricity, longitude of pericenter ω in degrees, and time of periastron passage τ in JD-245000, for each planet, respectively, as well as the offsets. The fit quality is measured in terms of reduced $(\chi^2_\nu)^{1/2}$ and an rms.

The best fit to the two-planet model yields $(\chi^2_\nu)^{1/2} = 1.63$ and an rms $= 11.5$ ms^{-1}. The four-planet model could not converge on any solution in which the RV contribution from all planets exceeded the mean uncertainty of the measurements (assuming detectable masses), and therefore could not produce any reasonable fit to the data. However, as we will see below, the three-planet model gives statistically better fits to the data, so we will focus on it.

We found the best three-planet fit yields $(\chi^2_\nu)^{1/2} = 1.28$ and drops the rms to $= 9.4$ ms^{-1}, which represent a significant improvement over those of the two-planet fit. The three-planet fit, given in terms of parameter tuples is the following: (113.296, 51.641, 0.640, 175.318, 1671.231) for planet b, (13.226, 277.378, 0.351, 294.266, 4221.105), for the new planet d, and (108.5127, 2433.177, 0.331, 275.455, 3497.965) for planet c. The velocity offsets are $(-2.94, 3.66, -6.01)$ ms^{-1} for ELODIE, CORALIE and HET, respectively. Curiously, the period of the new planet d is $\sim$ 277 days, and is significantly different from the best-fit solution quoted in Bean et al. (2008), who report $P_d = 347$ days. This discrepancy most likely results from our different handling of the errors, as well as the inclusion of 10 additional data points. However, we also find a similar local minimum at $P_d = 349$ days (close to the fit in Bean *et al.* 2008), as well as $P_d = 900$ days, but with large e_d (0.6).

Because $e_{\rm d}$ can reach large values in the Keplerian fit we cannot assume that the best-fit configurations are dynamically stable. To account for the mutual interactions and test for stability, the ensemble of Keplerian solutions has been used as initial conditions in an N-body model (Laughlin & Chambers 2001). The Keplerian fits are not a good representation of the system because they lead to significant degradation of $(\chi^2_\nu)^{1/2}$. Hence, we refined these Keplerian fits to account for the mutual interactions. In addition, we tested formal stability (as understood through chaotic or quasi-periodic character of orbital configurations) of these refined solutions with MEGNO (Cincotta & Simó 2000; Cincotta, Giordano & Simó 2003; Goździewski *et al.* 2001). MEGNO has been computed over $3 \cdot 10^4$ orbital periods of the outermost planet which is long enough to account for the destabilizing influence of short-term mean motion resonances.

The dynamical analysis reveals two narrow strips of dominant solutions around $a_d = 0.89$ AU ("Fit 1", $(\chi^2_\nu)^{1/2} = 1.30$ with rms 9.55 ms^{-1}) and 1.02 AU ("Fit 2", $(\chi^2_\nu)^{1/2} = 1.32$ with rms 9.58 ms^{-1}) (see Fig. 1), with some hint of a solution around 2 AU. These are the Newtonian fits to the data. Table 1 presents these two fits, where m is mass, M is mean anomaly and T_0 is the epoch of the first observation, JD 2,445,823.5570. To be certain that

the MEGNO signature is well time-calibrated (in the sense that it will identify instabilities generated by strong mean motion resonances), we integrated the best 16 solutions with the Bulirsh-Stoer integrator from the MERCURY package (Chambers 1999) over 100 Myr each. All survived without any noticeable change of the regular character. Fig. 2 shows stable and chaotic regions near the two best stable fits.

Table 1 - Best-fits Orbits and Masses for the Planets of HD 74156

Fit	Planet	m (M_{Jup})	a (AU)	e	ω (°)	$M(T_0)$ (°)
1	b	1.847	0.292	0.635	175.32	210.90
	d	0.396	0.892	0.240	226.50	334.00
	c	7.774	3.822	0.361	272.66	328.06
2	b	1.847	0.292	0.629	176.45	211.64
	d	0.412	1.023	0.227	191.81	67.51
	c	7.995	3.848	0.426	262.17	340.20
3[a]	b	1.882	0.292	0.640	175.37	210.88
	d	0.407	0.893	0.281	228.76	334.81
	c	7.830	3.818	0.363	272.364	327.39
4[a]	b	1.882	0.292	0.635	176.20	211.55
	d	0.409	1.022	0.262	177.66	78.73
	c	8.176	3.853	0.427	261.25	341.43

[a] All planets in this fit have an inclination of 80°.

Finally, we tried to estimate a limit for the inclination of the three-planet system. We selected a sample of 200 Newtonian solutions from the previous search. For each fit we increased the system's inclination in steps of 1° and then refined this fit with the Levenberg-Marquart scheme. Simultaneously, we also tested stability of these fits with MEGNO. Obviously, the inclination of the system is unconstrained. Overall, the N-body model does not improve the formal $(\chi^2_\nu)^{1/2}$ of Keplerian – but it is important for the dynamical analysis and for finding stable configurations. Moreover, the stable fits can be found down to $i \sim 40°$ with simultaneous rough scaling with the masses by the Doppler factor $f = 1/\sin i$. We also note that the border of stable motions for e_d is at ~ 0.3. Still, fits with $a_\mathrm{d} \sim 0.89$ AU ("Fit 3", $(\chi^2_\nu)^{1/2} = 1.30$ with rms 9.6 ms^{-1}) yield a slightly smaller $(\chi^2_\nu)^{1/2}$ than solutions with $a_\mathrm{d} \sim 1.02$ AU ("Fit 4", $\chi^2 = 1.31$ with rms 9.66 ms^{-1}).

RB05 predicted a Saturn-mass planet was most likely to be discovered in the range $0.9 \lesssim a \lesssim 1.4$ AU, and $0 \leq e \lesssim 0.2$. The four most likely fits identified by this analysis show

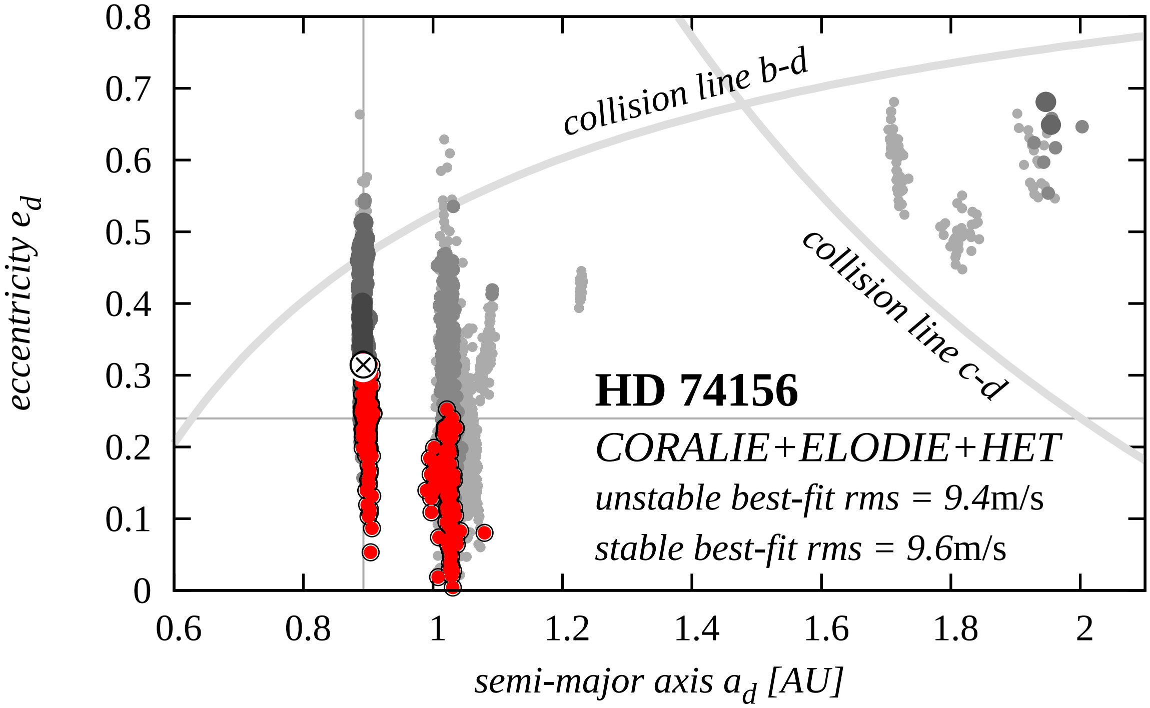

Fig. 1.— Fit parameters of the coplanar Newtonian model to the data published in Naef *et al.* (2004) and Bean *et al.* (2008). Osculating elements at the epoch of the first observation are projected onto the $(a_{\rm d}, e_{\rm d})$-plane. Gray curves are the collision lines of the orbits computed with the elements of the innermost and the outermost companions fixed at their best fit values. The best fit solution (Fit 1) is marked by the intersection of the horizontal and vertical lines. For reference, the best fit (unstable) configuration is marked with a white crossed circle. Light-gray circles are for fits with$(\chi^2_\nu)^{1/2} < 1.35$ (an rms limit of ~ 10 ms^{-1}). Darker gray circles are for solutions with $(\chi^2_\nu)^{1/2} < 1.33$ and $(\chi^2_\nu)^{1/2} < 1.31$, respectively. Stable fits are marked with red circles.

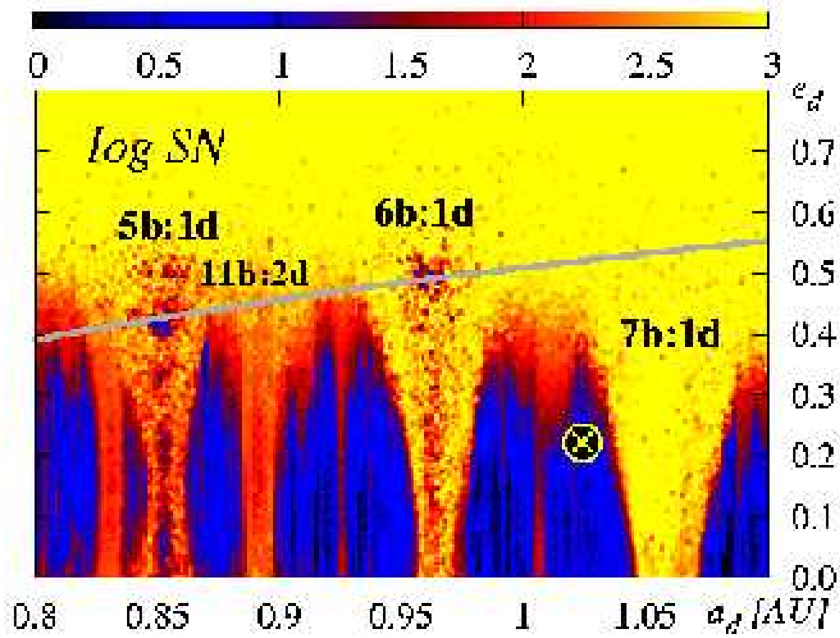

Fig. 2.— The dynamical map for configurations near Fit 2 in terms of the Spectral Number log(SN) (Michtchenko & Ferrraz-Mello 2001). The character of the solutions is color-coded: yellow means chaotic systems and black means regular systems. Fit 2 is marked with a crossed circle. Most significant mean motion resonances between the two innermost planets are labeled.

that the prediction of the PPS model has been borne out. HD 74156 d is the first extrasolar planet to have its mass and orbit predicted. Fits 1 and 3 have the same $(\chi_\nu^2)^{1/2}$ value, but Fit 1 has a slightly smaller rms, so it should be considered the best overall fit to the observations.

3. Discussion

In addition to HD 74156, similar predictions of new planets had been made for the systems 55 Cnc, HD 37124 and HD 38529 by BR04 and RB05. Subsequently, the orbital architectures of three of these four systems have been updated in ways that are consistent with the PPS picture.

A fifth planet was recently discovered in orbit about 55 Cnc in the stable zone identified in BR04 and RB05 (Fischer *et al.* 2008). This new planet, 55 Cnc f, is at the inner edge of the stable zone, and is consequently packed in with the inner three. 55 Cnc f is therefore also consistent with the PPS model. However, there is still room for additional planets in this system (Raymond & Barnes 2008). The HD 37124 planetary system was revised from two to three planets, on orbits markedly different from the initially-announced configuration (Vogt *et al.* 2005; see also Goździewski *et al.* 2008). The current best-fit orbits of the planets in HD 37124 (Goździewski *et al.* 2008) suggest the system is packed and is therefore also consistent with the PPS model. The final system considered in BR04 and RB05, HD 38529, has yet to produce another planet, but the observations presented in Moro-Martín *et al.* (2007) suggest there is no observational evidence for or against an additional planet in HD 38529.

The nature of the single planet systems appears at odds with the PPS model. About 85% of known exoplanets are currently observed to be the sole companion of their host star[1]. If the PPS hypothesis is to be believed, then we would naturally expect planetary systems should all be multiple. There are three possible explanations for the current observations of single planet systems in the context of the PPS hypothesis: 1) The orbits of additional companions have not been robustly detected yet, 2) the additional planets are too small to be detected, and/or 3) the additional planets have significant inclinations. Wright *et al.* (2007) find that at least 30% of single planet systems show evidence of additional companions. Therefore it may be that, as more data are obtained, the fraction of single planet systems will drop precipitously. Another possibility stems from the observed distribution of planet masses, which rises steeply at low mass (Marcy *et al.* 2005). This result implies many planets may lie in these gaps, but surveys lack the precision to detect them. A third possibility is that mutual inclinations could be significant, resulting in only one detectable planet. For

[1]http://exoplanets.org

example, Marzari & Weidenschilling (2002) showed that scattering can pump up inclinations to large values while simultaneously increasing eccentricities. Therefore it may be that some systems appear to have only one planet because the other planets are too inclined to the line of sight to be detected by radial velocity surveys.

In addition to packed exoplanet systems, numerical experiments testing the stability of the giant planets in our Solar System suggest that they, too, are packed (*e.g.* Varadi *et al.* 1999, Michtchenko & Ferraz-Mello 2001; Barnes & Quinn 2004). The apparently high frequency of packed giant planet systems naturally motivates research to identify more planets in stable locations. Stability analyses show that several systems stand out as non-packed. A simple method to determine the proximity to dynamical instability, β, is described in Barnes & Greenberg (2007) based on the concept of "Hill stability" (Marchal & Bozis 1982; Gladman 1993). In Barnes & Greenberg's formulation, the stability boundary lies at $\beta = 1$, and stable systems require $\beta > 1$, except in the case of mean motion resonances (note that numerical analyses of these systems do suggest that they, too, are packed [Goździewski & Maciejewski 2001; Barnes & Quinn 2004; Barnes & Greenberg 2007]). Barnes & Greenberg 2007 estimated that when $\beta > 2$, then the system may contain an additional planet, but more work is needed to verify this possibility.

Several two-planet systems are known with β values greater than 2 (note that HD 38529 has a β value of 2.07). HD 217107 (Vogt *et al.* 2005) has a β value of 7.1, HD 68988 (Wright *et al.* 2007) has $\beta = 12.5$ and HD 187123 (Wright *et al.* 2007) has $\beta = 15.3$[2]. These systems have gaps that are probably large enough to contain multiple additional companions. We also note, however, that the outer companions of the latter two systems have orbits which are poorly constrained. Additionally, the inner planets have been tidally circularized (Rasio *et al.* 1996) and consequently may have formed with significantly larger values of e and a (Jackson*et al.* 2008). It may be many years before the known planets' orbits are measured with significant precision, let alone unknown companions are detected.

4. Conclusions

The correct prediction of the mass and orbit of HD 74156 d is a major step forward in our understanding of the nature of exoplanets. It also represents the first successful prediction of the mass and orbit of a planet since Neptune was predicted independently by LeVerrier and Adams in the 1840s. Although their approach was markedly different than that of BR04 and RB05, both predictions relied on the dynamical properties of other planets in the system.

[2]see http://www.lpl.arizona.edu/∼rory/research/xsp/dynamics/ for an up-to-date table of β values.

As mentioned in § 1, of the first 6 multiple extrasolar planet systems detected, only HD 74156 appeared to not be dynamically packed. The detection of planet d by Bean *et al.* (2008), and its confirmation presented in § 2, now means that the first 6 multi-planet systems to be detected were packed. Although there may be some bias toward detecting packed systems because radial velocity surveys are more likely to find planets close to their host star, HD 74156 d was a difficult planet to detect because of its low mass. Therefore its detection is a strong indicator that most, if not all, multiple planet systems are dynamically packed. But, of course, future observations will ultimately reject or confirm the PPS theory. We encourage observers to focus on HD 38529, HD 217107, HD 68988 and HD 187123 in order to determine if additional companions lay between the two that are known. Furthermore, additional companions need to be detected in one-planet systems.

We also encourage future work to continue to explore mechanisms which may lead to packed planetary systems. It could be that packing is a natural consequence of planet formation (Laskar 2000; Scardigli 2007). One such model is the dynamical relaxation of planets in a damped medium (Adams & Laughlin 2003), but more work is needed to verify this possibility.

The detection of HD 74156 d suggests that planet formation is an efficient process and that planets may be common. We have suggested several systems which are important litmus tests for the PPS theory. We also encourage programs aimed at detecting astrometric signals from planets that have been detected by radial velocity surveys.

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